

**MISSION STUDY FOR GENERATION-X: A LARGE AREA AND HIGH
ANGULAR OBSERVATORY TO STUDY THE EARLY UNIVERSE**

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Annual Report

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Annual Technical Report

Grant: NNG04GK28G

Generation-X Vision Mission Study

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1 Introduction

In this report we provide a summary of the technical progress achieved during the last year under grant NNG04GK28G, "Generation-X Vision Mission Study". In addition, we provide a brief programmatic status.

The Generation-X (*Gen-X*) Vision Mission Study investigates the science requirements, mission concepts and technology drivers for an X-ray telescope designed to study the new frontier of astrophysics: the birth and evolution of the first stars, galaxies and black holes in the early Universe. X-ray astronomy offers an opportunity to detect these via the activity of the black holes, and the supernova explosions and gamma-ray burst afterglows of the massive stars. However, such objects are beyond the grasp of current missions which are operating or even under development. Our team has conceived a *Gen-X* Vision Mission based on an X-ray observatory with 100 m² collecting area at 1 keV (1000 times larger than Chandra) and 0.1 arcsecond angular resolution (several times better than Chandra and 50 times better than the Constellation-X resolution goal). Such a high energy observatory will be capable of detecting the earliest black holes and galaxies in the Universe, and will also study extremes of density, gravity, magnetic fields, and kinetic energy which cannot be created in laboratories.

In our study we develop the mission concept and define candidate technologies and performance requirements for *Gen-X*. The baseline *Gen-X* mission involves four 8 m diameter X-ray telescopes operating at Sun-Earth L2. We trade against an alternate concept of a single 26 m diameter telescope with focal plane instruments on a separate spacecraft. A telescope of this size will require either robotic or human-assisted in-flight assembly. The required effective area implies that extremely lightweight grazing incidence X-ray optics must be developed. To achieve the required areal density of at least 100 times lower than for Chandra, we study 0.2 mm thick mirrors which have active on-orbit figure control. We also study the suite of required detectors, including a large FOV high angular resolution imager, a cryogenic imaging spectrometer and a reflection grating spectrometer.

2 Programmatic Status

Overall the effort under this grant is proceeding within the planned budget. A brief summary of the major programmatic actions is provided.

Following receipt of funding on 4 June 2004 a subcontract was placed with MIT for effort in support of *Gen-X* detector and student study work. The subcontract was placed on 13 August 2004 with a value of \$25K. Work on both the instrument definition and

student study has been proceeding on schedule. In keeping with a grant objective, the student work is being done by qualified students working under faculty supervision. A presentation of this work to date was made by MIT to the *Gen-X* team at SAO

Following discussions with GSFC IMDC, \$35K of funding is being re-programmed from a combination of existing *Gen-X* funds at GSFC, and SAO engineering labor to fund a *Gen-X* Study by the GSFC IMDC. The IMDC offered a reduced cost for a study that focused on our 4-satellite fixed optical bench approach. This study clearly complemented the JPL Team-X study what centered on our formation flying approach, and added significantly to our overall study and final report.

A subcontract for \$7K is being placed with the University of Puerto Rico in mid-April. This subcontract funds a student engineering study of a number of candidate optical bench designs identified during the IMDC study.

3 Technical Progress

We have considered several possible realizations of each of the single-telescope and multiple-telescope concepts, and selected one particular definition of each in order to proceed with our study. This involved specifying the inner and outer diameter, the segment length, number of shells, and shell separations for a single telescope, and for each of the four telescopes in the multiple satellite case. Such parameters would be optimized in a later design stage, but at present do not effect our feasibility study.

We have been studying issues related to the key technology of adjustment of the mirror figure on-orbit. We have started computer simulations of what effect a single piezo-electric actuator has on a thin, flat sheet. We plan to extend this finite element analysis to several piezo actuators, in order to assess the cross talk. We are developing a concept for acquiring the data needed to perform the on-orbit adjustment. This involves moving a high resolution detector sufficiently forward of the focal plane that the individual shells image a bright celestial X-ray source as distinct rings. The widths and radii of these rings, resolved azimuthally, must contain the available information.

The two items above allowed us to define two specific configurations which we used as inputs for the Team-X and IMDC studies discussed below.

3.1 NASA Design Center Studies

We performed mission design feasibility studies with both the JPL Advanced Projects Design Team (Team-X) and the GSFC Integrated Mission Design Center (IMDC). We selected a different mission concept for each team to study to ensure coverage of the major mission architecture trades identified for our study. Team-X studied the concept of a single 20-meter-diameter optic on one spacecraft with the focal-plane instruments and reflection grating assembly on a separate spacecraft flying in formation. The IMDC studied the concept of six identical spacecraft with an 8-meter-diameter optic and focal-plane instruments attached with a deployable boom.

3.1.1 JPL Team-X Study

Preparatory telephone meetings for the Team-X study were held in November and early December 2004. The study sessions were held on December 14, 16, and 17 with R. Brissenden and W. Podgorski supporting in person on December 14, D. Schwartz supporting in person on December 16, and other team members supporting via telephone. A key result of the Team-X study was a trade that stated it would be best to launch the optic as a single unit, folded to fit into a launch fairing, rather than as several units that would require on-orbit assembly. This approach does require the development of a new heavy-lift capability. The deployed optics spacecraft would then rendezvous and dock in low Earth orbit with three propulsion stages that would provide the means for getting to Sun-Earth L2. The instrument spacecraft could be sent directly to L2 to rendezvous with the optics spacecraft using current launch capability. The final report from the Team-X study has been delivered, is being reviewed, and its contents will be used in the generation of the final report of this study.

3.1.2 GSFC IMDC Study

The IMDC study began with preparatory meetings in January 2005; the study sessions were held daily during the February 7-11, 2005 week. R. Brissenden and D. Schwartz supporting the initial kick-off meeting in person and E. Figueroa in person throughout the week. Other team members supported the sessions via telephone. The IMDC study produced a configuration for the six identical spacecraft that could fit within the Delta 4050H launch vehicle 19.8 m fairing; however, the weight of the spacecraft with standard margins exceeded the capability of the booster by roughly 8%. Given the early stage in the design process, this was not considered a major issue by the team. We await the final report from the IMDC and expect to incorporate its results in the final report of this study.

3.2 Science Requirements Refinement

In conjunction with the design work our science team has proceeded towards refining the *Gen-X* science requirements.

The *Gen-X* proposal goals are highly active areas of research. It is important then to follow this research and to assess the robustness of the quantitative results to understand how firm the basis of the *Gen-X* requirements is. The *Gen-X* study team has been keeping up with developments, both theoretical and observational that will impact *Gen-X* design parameters. For example theories of black hole formation in the early universe from the first generation of stars are becoming more realistic and so refining their likely mass range. If these masses go down, then the baseline *Gen-X* area would need to go up to match the lower Eddington limit of the smaller resultant black holes. So far the masses of a few hundred solar masses appear robust. Similarly, the timescale on which to measure General Relativistic reverberation effects in nearby Active Galaxies depends on the masses of their central black holes. In the last two years the number of such well-determined masses has grown rapidly and now stands at three dozen. Overall the masses

are smaller than expected, a sufficient decrease to become a driver on the *Gen-X* area, though not enough to warrant an increase in the baseline. These masses are also now robust to a factor of 2 – 3, which is not enough to require altering the baseline. Similar examples are found in most areas of *Gen-X* Key Science Objectives.

The team has also considered observing program strategies and how these might affect science requirements. *Gen-X* is 1000 times faster than Chandra at collecting photons from a given source. Hence a 1 Ms ‘Legacy Class’ Chandra program can be accomplished by *Gen-X* in 20 minutes. Chandra has shown that there are large numbers of objects for which Megasec exposures would yield great science but, necessarily, few of these can be completed even in the whole Chandra mission. We imagine then a ‘snapshot’ mode of many 1 ks–2 ks *Gen-X* observations, each yielding a quality of data scarcely attainable today, to be accomplished by having a pool of observations that will be done as and when a target lies ‘en route’ to another, longer, one. HST has a similar program that increases observing efficiency. Consideration of this observing mode elicits a new requirement for *Gen-X*: ‘settling time’. Distinct from slew rate, settling time is how long it takes *Gen-X* to begin acquiring science data once a slew is over. Settling time includes: the time to damp out vibrations that are too large, the time to acquire guide stars, any instrument setup time. The settling time should be small compared with the shortest observation, i.e. <100–200 s. We will now feed this objective back into the mission studies in order to determine if this is a practicable requirement.

3.3 Community Meeting and Feedback

A community workshop was held at the HEAD meeting of the AAS in New Orleans on 8 December 2004. The following presentations were made at the workshop:

The <i>Gen-X</i> Vision Mission Study	Roger Brissenden
<i>Gen-X</i> : Science Objectives	Jeremy Heyl
<i>Gen-X</i> Mission Concept	Dan Schwartz
<i>Gen-X</i> Technology Drivers	William Zhang
<i>Gen-X</i> Telescope Design and Trades	Paul Reid
Science Instruments for <i>Gen-X</i>	Mark Bautz

The workshop was well attended with over 200 participants and useful feedback was obtained both during and after the meeting. Of note was the suggestion to consider increasing the study baseline Field Of View (FOV) from 5 arcmin to 15 arcmin to make best use of the very large collecting area. A larger FOV increases the power of all surveys, and going to 15 or even 20 arcmin will improve imaging of supernovae remnants and clusters of galaxies. In addition, we were urged to consider an increased counting rate capacity, shown as $100/(\text{s pixel})$ and $10^4/(\text{s field-of-view})$ as a baseline, driven by the fact that the brightest Chandra sources reach of order $10^2/\text{s}$ implying that *Gen-X* will reach of order $10^5/\text{s}$. This feedback has been incorporated into our study.

3.4 Student Involvement

3.4.1 MIT

As a component of their subcontract, MIT has been tasked to perform a study of alternative and innovative formation flying techniques. The study, led by Prof. David Miller is near completion and was reported on in a presentation on 14 Feb 2005. In his presentation, "A Comparison between Structurally Connected, Propellant Based Formation Flying and Electromagnetic Formation Flying Spacecraft for the *Gen-X* mission", Miller compared the cost-effectiveness of three methods of holding the *Gen-X* detectors behind the primary: a traditional structural truss (optical bench), propellant based formation flying (PFF), and electromagnetic formation flying (EMFF). Miller and his students concluded that formation flight provides a number of advantages over a fixed optical bench including reconfigurability, straightforward replacement upgrade of the detectors, rematching of the detectors with the primary in the event of failures, ease of launch packaging and deployment. In comparing EMFF with PFF, the approaches were comparable in terms of mass and lighter than fixed optical bench, and that EMFF eliminates contamination issues. EMFF becomes more favorable when high agility (high ΔV) is required. These results are presently being incorporated into the Study report trades.

3.4.2 University of Puerto Rico

A study has been initiated with the University of Puerto Rico (UPR) under the direction of Dr. Vijay Goyal of the Mechanical Engineering Department. Dr. Goyal and his students will perform a study of the design requirements for the boom that connects the optics portion of the *Gen-X* spacecraft to the science instrument portion. Using the baseline design for the boom from the GSFC IMDC study, the UPR students will perform an analysis of how the stiffness and modes of vibration change as the boom parameters and deployment methods are changed. The results of the study will be provided as a report and will be incorporated in the Study report.

4 Plans for Remaining Work

The remaining work will focus on the writing of the final report. With both the JPL Team-X and GSFC IMDC studies complete, community workshop held, and science requirements under assessment, the necessary materials are now available. A draft report is expected to be complete and under internal review by the team by Jun 15. A final report is expected by the end of the summer.

5 Summary of Papers and Presentations

The following papers and presentations have been published during the course of this work. Copies of the papers can be found at: <http://genx.cfa.harvard.edu/Genx/GenxPapers>.

1. Figueroa-Feliciano, E., Cameron, C., Bautz, M., Brissenden, R., Elvis, M., Fabbiano G., Gorenstein, P., Petre, R., Reid, P., Schwartz, D., White, N., Zhang, W., "Generation-X X-ray Observatory Vision Mission and Technology Study", Beyond Einstein: From the Big Bang to Black Holes, SLAC, Stanford University, May 2004.
2. Bautz, M. W., "Science Instruments for Generation-X", *Bul. AAS*, **36**, No. 3, 2004.
3. Brissenden, R. J., "The Generation-X Vision Mission Study", *Bul. AAS*, **36**, No. 3, 2004.
4. Heyl, J. S., "Gen-X: Science Objectives", *Bul. AAS*, **36**, No. 3, 2004.
5. Reid, P., "Generation-X Telescope Design and Trades", *Bul. AAS*, **36**, No. 3, 2004.
6. Schwartz, D. A., "The Gen-X Mission Concept", *Bul. AAS*, **36**, No. 3, 2004.
7. Zhang, W., "Generation-X Mission Technology Drivers", *Bul. AAS*, **36**, No. 3, 2004.
8. Cameron, R., Bautz, M., Brissenden, R., Elvis, M., Fabbiano, G., Figueroa-Feliciano, E., Gorenstein, P., Petre, R., Reid, P., Schwartz, D., White, N., Zhang, W., "Generation-X: Mission and Technology Studies for an X-Ray Observatory Vision Mission", *Astronomical Telescopes and Instrumentation, SPIE*, June 2004
9. Reid, P., Cameron, R., Cohen, L., Elvis, M., Gorenstein, P., Jerius, D., Petre, R., Podgorski, W., Schwartz, D., Zhang, W., "Constellation-X to Generation-X: Evolution of large collecting area, moderate resolution grazing incidence x-ray telescopes to larger area, high resolution, adjustable optics", *Astronomical Telescopes and Instrumentation, SPIE*, June 2004
10. Brissenden, R., Cameron, R., Fabbiano, G., White, N., Zhang, W., "The Generation-X X-ray Observatory Vision Mission and Technology Study", *AIAA*, September 2004.
11. Brissenden, R., "The Generation-X Vision Mission Study", Presentation to the joint Origins/Structure Evolution of the Universe, Greenbelt MD, 8 November 2004.
12. Schwartz, D., "The Generation-X Vision Mission", Presentation to the Strategic Roadmap Committee #8, by Dan Schwartz, Greenbelt MD, 15 March 2005.

In addition to the papers listed above, the following paper is in preparation:

Windhorst, R., Bautz, M., Brissenden, R., Elvis, M., Fabbiano, G., Figueroa-Feliciano, E., Juda, M., Schwartz, D., White, N., Zhang, W., "Generation-X Science", First Light and Reionization: Theoretical Study and Experimental Detection of First Luminous Sources, U.C. Irvine, May 19-21, 2005, in preparation.